

# Broad Emission Line Regions in AGN: the Link with the Accretion Power

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## ABSTRACT

We present a model which relates the width of the Broad Emission Lines of AGN to the Keplerian velocity of an accretion disk at a critical distance from the central black hole. This critical distance falls in a region bounded on the inward side by the transition radius between the radiation pressure and the gas pressure dominated region of the accretion disk and on the outward side by the maximum radius below which a stabilizing, radially accreting and vertically outflowing corona exists.

We show that in the framework of this picture the observed range of  $H\beta$  FWHM from Broad Line to Narrow Line type 1 AGN is well reproduced as a function of the accretion rate. This interval of velocities is the only permitted range and goes from  $\sim 20,000 \text{ km s}^{-1}$  for sub-Eddington accretion rates, to  $\sim 1,000 \text{ km s}^{-1}$  for Eddington accretion rates.

*Subject headings:* accretion, accretion disks — galaxies: active — quasars: emission lines

## 1. Introduction

Broad Emission Lines (BELs) are probably ubiquitous in AGN, being unobserved only when a good case can be made for their obscuration by dust (type 2 AGN) or their being swamped by beamed continuum (Blazars). This suggests that the presence of Broad Emission Line Clouds (BELCs) in the AGN environment is closely related to the mechanisms which are responsible for the quasar activity. Shakura & Sunyaev (1973, hereinafter SS73) already noted that a high velocity, high density wind of ionized matter may originate from the accretion disk (a suggestion greatly elaborated by Murray et al., 1995), at a radial distance where the radiation pressure becomes comparable to the gas pressure. Witt, Czerny and Zycki (1997, hereinafter WCZ97) studied a radially co-accreting disk/corona system (which stabilizes the, otherwise thermally unstable, radiation pressure dominated region of a Shakura-Sunyaev disk - SS-disk), and demonstrated that a transonic vertical outflow from the disk develops where the fraction of total energy dissipated in the corona is close to the maximum. In a revised version of this model (Czerny et al., 1999, in preparation), which includes evaporation from the disk, this solution continues to hold for accretion rates higher than a minimum value, below which evaporation inhibits the formation of the wind.

Reverberation studies of the BELs in many Seyfert 1 galaxies (e.g. Wandel, Peterson & Malkan, 1999; hereinafter WPM99) indicate that the gas of the BELCs is photoionized, and that its physical state, from one object to another, covers a rather narrow range of parameter space (in column density, electron density, ionization parameter). It is also clear (Krolik et al., 1991; Peterson et al., 1999) that within a single object the BELCs are stratified, with the highest ionization lines being also the broadest. This accords with the photoionization hypothesis and with the idea that the BELs are broadened by their orbital Keplerian motion around the central source (Peterson & Wandel, 1999).

On the other hand the BELs do not at all have the same dynamical properties in all objects. A broad distribution of line widths from  $\sim 1,000 \text{ km s}^{-1}$  (in Narrow Line Seyfert 1 galaxies, NLSy1) to  $\sim 20,000 \text{ km s}^{-1}$  (in the broadest broad line type 1 AGN) is present. A model by Wandel (1997) attempts to forge a physical link between the breadth of the permitted optical emission lines of type 1 AGN and the steepness of their X-ray continuum: a steeper X-ray spectrum has stronger ionizing power, and hence the BELR is formed at a larger distance from the central source, where the velocity dispersion is smaller, and so produces narrower emission lines. Alternatively, Laor et al. (1997) use a dynamical argument to suggest that small emission line widths are direct consequence of large  $L/L_{Edd}$ .

Here we propose that a vertical disk wind, originating at a critical distance in the accretion disk, is

the origin of the BELCs and that the widths of the BELs are the Keplerian velocities of the accretion disk at the radius where this wind arises. The disk wind forms for external accretion rates higher than a minimum value below which a standard SS-disk (SS73) is stable and extends down to the last stable orbit. The model explains the observed range of FWHM in the BELs of AGN as a function of a single physical quantity connected with the AGN activity: the accretion rate. In §2 we present our model, and show the basic equations which support our findings. In §3 we discuss the observational consequences and compare with existing data.

## 2. The Model

The three main ingredients of our model are: (a) the transition radius  $r_{tran}$ , derived by setting equal the radiation pressure at  $r < r_{tran}$  and the gas pressure at  $r > r_{tran}$ , in a standard SS-disk (SS73):

$$r_{tran} f^{-16/21} \simeq 15.2 (\alpha m)^{2/21} \left( \frac{1}{\eta} \dot{m} \right)^{16/21}, \quad (1)$$

(b) the approximate analytical relationship giving the fraction of energy dissipated in the corona, in a dynamical disk/corona configuration (WCZ97):

$$(1 - \beta) \simeq 0.034 (\alpha f \frac{1}{\eta} \dot{m})^{-1/4} r^{3/8}, \quad (2)$$

and (c) the maximum radius below which a stable co-accreting disk/corona configuration can exist, obtained by setting  $\beta = 0$  (WCZ97):

$$r_{max} f^{-2/3} \simeq 8,000 \left( \alpha \frac{1}{\eta} \dot{m} \right)^{2/3}. \quad (3)$$

In the above equations we have used dimensionless quantities:  $m = M/M_\odot$ ,  $\dot{m} = \dot{M}/\dot{M}_{EDD}$ ,  $r = R/R_0$ , with  $\dot{M}_{EDD} = 1.5 \times 10^{17} \eta^{-1} m \text{ g s}^{-1}$ , and  $R_0 = 6GM/c^2$ , for a non-rotating black hole; here  $\eta$  is the maximum efficiency. Finally,  $f$  gives the boundary conditions at the marginally stable orbit:  $f = f(r) = (1 - r^{-0.5})$ .

We note that (with the adopted units)  $r_{max}$  does not depend on the mass, while  $r_{tran}$  depends only very weakly on it. However both these critical radii depend on the accretion rate and, interestingly, with similar powers. This results in a quasi-rigid radial shifting of the region delimited by these two distances as the accretion rate (in critical units) varies. From equations 1 and 3 we can estimate the total radial extent of this region to be of the order of  $\sim 10$  times  $r_{tran}$ , for  $m = 10^8$  and  $\dot{m} = 1$ <sup>1</sup>. Equation 1

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<sup>1</sup> The radial extent of the vertical outflow containing the BELCs, however, is smaller than this, being constrained by the weighting function  $(1 - \beta)$  (equation 2, WCP97. See below).

allows us to define the minimum external accretion rate needed for a thermally unstable radiation pressure dominated region to exist. From the condition  $r > 1.36$  (the limit of validity of the SS-disk solution) we have:  $\dot{m} \gtrsim \dot{m}_{min}(m) \simeq 0.3\eta(\alpha m)^{-1/8}$ . Throughout this paper we assume  $\eta = 0.06$ , and a viscosity coefficient of  $\alpha = 0.1$ , which give a minimum external accretion rate of  $\dot{m}_{min} \sim (1-4) \times 10^{-3}$ , for  $m$  in the range  $10^6 - 10^9$ . At lower accretion rates a SS-disk (SS73) is stable down to the last stable orbit: we propose that all the available energy is dissipated in the disk and no radiation pressure supported and driven wind is generated. AGN accreting at these low external rates should show no BELs in their optical spectra. For accretion rates  $\dot{m} \gtrsim \dot{m}_{min}$  a SS-disk is unstable (Lightman & Eardley, 1974) and a stabilizing, co-accreting “disk/corona + outflow” system forms (WCZ97). The fraction of energy dissipated in the corona, and powering the vertical outflow, is maximum at  $r_{max}$  and decreases inward following equation 2 (see also Fig. 6 in WCZ97). At radii smaller than  $r_{tran}$  the available energy is almost equally divided between the disk and the corona (WCZ97). We then adopt an averaged radius  $r_{wind}$  for the transonic outflow (and so for the BELRs), obtained weighting the radial distance by  $(1 - \beta)$  - equation 2 - , between  $r_{tran}$  and  $r_{max}$ . We computed  $r_{wind}$  numerically for several values of  $m$  and  $\dot{m}$ .

In the next section we discuss the implications of our model for linking the gas of the BELR in type 1 AGN and the accretion mechanism.

## 2.1. Dynamical Properties

We calculated the orbital velocities at  $r_{wind}$  under the Keplerian assumption:  $\beta(r_{wind}) = v/c = (6r_{wind})^{-1/2}$ . We then transformed these velocities to Full Width Half Maximum (FWHM) values of the lines emitted by these clouds of gas using the relationship:  $\text{FWHM} = 2(\langle v^2 \rangle)^{1/2}$  (Netzer, 1991), where  $(\langle v^2 \rangle)^{1/2} = v/\sqrt{2}$  is the averaged Keplerian velocity in a cylindrical geometry. In Figure 1 we show the relationship between the accretion rate (in the range  $\dot{m}_{min}(m) - 10$ ) and the expected  $\text{FWHM}(r_{wind})$  (solid, thick curves) and  $\text{FWHM}(r_{max})$  (dashed, thin curves), for  $m = 10^6, 10^7, 10^8, 10^9$ . These curves are independent on the mass of the central black hole, and so they overlap in the diagram of Figure 1. However, for each curve, the maximum FWHM reachable depends on the mass, through the limit imposed by the minimum external accretion rate  $\dot{m}_{min}(m)$  needed for an unstable SS-disk to exist. At the bottom of the plot the four horizontal lines indicate these values of  $\dot{m}_{min}(m)$ . The parameter space delimited by the dashed and solid curves of Figure 1 gives a possible range of FWHM at a given accretion rate, so allowing,

at least partly, for a stratification of the BELCs in a single object <sup>2</sup>. Finally, we marked two different regions in the diagram of Figure 2: (a) for accretion rates  $\dot{m} < 0.2$  (sub-Eddington regime) the predicted FWHM are quite broad ( $\gtrsim 4,000 \text{ km s}^{-1}$ ), and similar to those typically observed in broad line type 1 AGN; (b) for  $\dot{m} = 0.2 - 3$  (Eddington to moderately super-Eddington) the corresponding FWHM span the interval  $\sim 1,000 - 4,000 \text{ km s}^{-1}$ , which contains the value of  $\text{FWHM} = 2,000 \text{ km s}^{-1}$  used to separate the two classes of broad line type 1 AGN and NLSy1. Hence our model predicts that narrow line type 1 AGN accrete at higher accretion rates compared to broad line objects, as in the Pounds et al. (1995) suggestion. However, the mass of the central black hole in NLSy1 does not need to be smaller than that of broad line type 1 AGN, which reconciles the NLSy1 paradigm with the recent results of WPM99 and the mass estimate for the NLSy1 galaxy TON S180 (Mathur S., private communication).

### 3. Comparison with Observations

Figure 3 shows an analogous and complementary diagram to Figure 2, where we plot  $r_{wind}$  in physical units on the Y-axis. The four mostly horizontal curves correspond to the four black hole masses  $m = 10^6, 10^7, 10^8, 10^9$ , with the accretion rate increasing from the bottom-right to the top-left of the diagram. The four vertical lines correspond to four values of the accretion rate  $\dot{m} = 0.01, 0.1, 1, 10$ , with black hole mass increasing from the bottom to the top. The space delimited by this grid contains all the allowed range of distances and orbiting velocities of the BELCs in this model. We also show a horizontal band which delimits the typical observed BELR sizes (WPM99). Superimposed on this diagram, we plot the recent measurements of distance and FWHM reported by WPM99 and obtained by using the reverberation-mapping technique. The points are numbered following the order of Table 2 in WPM99. For each point the grid of Figure 2 allows one to uniquely determine the predicted accretion rate and black hole mass. We calculated the ratio  $\xi$  between the measured (WPM99) dimensionless luminosity  $\ell = (L_{ion}/L_{Edd})$  and the predicted accretion rate.  $\xi$  is then a measure of the relative efficiency (compared to the maximum radiative efficiency  $\eta$ ):  $\xi = \epsilon/\eta$ , where  $\epsilon = L_{ion}/Mc^2$ ) with which the accretion power is

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<sup>2</sup>However, according to the model for the quasar structure proposed by Elvis (1999), a more complete and satisfactory explanation is that the high and low ionization BELs are actually produced in two separate regions of the outflow: in the vertical part, at a height  $z < r$  from the disk surface (high ionization lines), and in the radially displaced part (low ionization lines) located at  $z > r$  (WCZ97) and shadowed by the vertically flowing gas (Elvis, 1999).

converted into ionizing luminosity. We found that  $\xi$  is correlated with the measured mass of the central black hole:  $\xi = 10^{-(0.4 \pm 0.9)} \times M_8^{(1.00 \pm 0.14)}$ ,  $R = 0.68$ , corresponding to a probability of  $P(>R;N=16) = 0.4\%$  (Figure 3. We do not consider here the tree objects of the WPM99 sample for which only upper limits on the central black hole mass were available). The correlation is still significant ( $R = 0.62$ ,  $P(>R;N=15) = 1.3\%$ ), when the object (NGC 4051) with the lowest mass and relative radiative efficiency is removed. This observational result is not an obvious consequence of our model and needs study. This correlation may explain why we do not see very-low mass AGN ( $\lesssim 10^4 M_\odot$ ): the efficiency in converting accretion power into luminosity may be too low for such objects.

#### 4. Testing the Model

##### 4.1. Observed Broad Line Widths

In the framework of our model, those AGN showing particularly broad emission lines (FWHM  $\sim 15,000 - 20,000 \text{ km s}^{-1}$ ) in their optical spectra are objects which are accreting at very low rate, close to but higher than  $\dot{m}_{min}(m)$ . Their expected ionizing luminosity is then given by  $L_{ion} \sim \xi(m) \dot{m}_{min}(m) L_{Edd} \sim 10^{43} M_8^{15/8} \text{ erg s}^{-1}$ , where  $M_8$  is the mass of the central black hole in  $10^8 M_\odot$ , and we used the correlation  $\xi \sim 0.4 M_8$ . The predicted ionizing luminosity at the minimum accretion rate are then  $L_{ion}(M_8 = 1) \sim 10^{43} \text{ erg s}^{-1}$  and  $L_{ion}(M_8 = 0.1) \sim 10^{41} \text{ erg s}^{-1}$ . AGN with strong and exceptionally broad emission lines (e.g. Broad Line Radio Galaxies, Osterbrock, Koski & Phillips, 1975; Grandi & Phillips, 1979) should then host a massive central black hole, of  $10^8 - 10^9$  solar masses. Lower mass black holes accreting at rates slightly higher than  $\dot{m}_{min}(m)$  may also have very broad optical emission lines, but they would be hard to detect due to their low contrast optical spectra.

Emission lines broader than  $\sim 20,000 \text{ km s}^{-1}$  should not exist for any plausible mass of black hole. This limit seems to be obeyed. FWHM  $\sim 20,000 \text{ km s}^{-1}$  are rare. Steiner (1981) lists 14 out of 147 AGN with FW-Zero-Intensity between 20,000 and 25,000  $\text{km s}^{-1}$  (only 3 with FW-Zero-Intensity  $> 23,000 \text{ km s}^{-1}$ ). The number with FW-Half-Maximum  $\sim 20,000 \text{ km s}^{-1}$  will be much less.

##### 4.2. Low Luminosity AGN

Nearby AGN with independently measured masses (see Ho, 1999) that imply accretion at rates lower than  $\dot{m}_{min}(m)$  should show no broad emission lines in their optical spectra.

NGC 4594 is a low luminosity ( $L_X \sim 3.5 \times 10^{40}$ , Nicholson et al., 1998) AGN/LINER with a spectroscopically well estimated mass of  $10^9$  solar masses for the central object (Kormendy et al., 1996). This gives a ratio between the X-ray (ASCA) and the Eddington luminosity of NGC 4594 of  $3 \times 10^{-7}$ . In our model no BELR should exist at this low  $L/L_{Edd}$ . Nicholson et al. (1998) showed that no broad H $\alpha$  was present in the HST spectrum of NGC 4594. From the ASCA spectrum they also put an upper limit on the column density of cold absorbing gas of  $2.9 \times 10^{21} \text{ cm}^{-2}$ . This is much lower than the amount of gas which would be needed to obscure the putative BELR. Nicholson et al. (1998) conclude that there is no BELR in NGC 4594. All this is in good agreement with the predictions of our model (see §4): if the object has a mass of  $10^9 M_\odot$ , then the expected luminosity for the minimum accretion rate  $\dot{m}_{min}(m)$  is  $\sim 7 \times 10^{44} \text{ erg s}^{-1}$ . An accretion rate of  $\dot{m} \sim 5 \times 10^{-5} \times \dot{m}_{min}(m)$  would then be necessary to obtain the observed X-ray luminosity of  $L_X \sim 3.5 \times 10^{40} \text{ erg s}^{-1}$  (Nicholson et al., 1998), at which no BELR is predicted to exist.

Ho et al. (1997) searched for BELRs in a sample of 486 bright northern galaxies. They found that among the 211 objects classified as having a Seyfert or LINER nucleus, only 46 ( $\sim 20\%$ ) have a detectable broad emission line component. Among these 46 the maximum H $\alpha$  measured is 4,200 km/s. The  $\sim 80\%$  of the sources in the sample with no broad H $\alpha$  are either (a) obscured (type 2) AGN, (b) low massive AGN with accretion rates slightly higher than  $\dot{m}_{min}(m)$  and in which the broad H $\alpha$  component is too broad to be measured in low-contrast spectra, or (c) AGN with high mass (and so visible) but with an accretion rate lower than  $\dot{m}_{min}(m)$ , and so with no BELRs (like NGC 4594). The remaining  $\sim 20\%$  of the sample with broad H $\alpha$  would be made of very low-mass AGN ( $\sim 10^5 M_\odot$ ), with quite normal (Sy1-like) accretion rate ( $\dot{m} \sim 0.1 - 0.5$ ), but (because of their low mass) with low-luminosity. The BELs in these objects would then be quite normal, and more easily detectable even in low contrast spectra.

## 5. Conclusions

We presented a simple model which tightly links the existence of the BELCs in type 1 AGN to the accretion mechanism. We derived the accretion rate and mass scaling laws for a mean distance on a stable SS-disk falling within the region delimited inward by the transition radius between the radiation pressure and the gas pressure dominated regions, and, outward, by the maximum radius below which a stabilizing co-accreting corona forms (WCZ97). We identify the BELR with a vertically outflowing wind of ionized matter which forms at this radius.

Our main findings are:

- The Keplerian velocity of the BELCs around the central black hole depends critically on the accretion rate. The entire observed range of velocities (FWHM) in type 1 AGN is naturally reproduced in our model allowing the accretion rate to vary from its minimum permitted value to super-Eddington rates.
- For accretion rates close to the Eddington value, the expected FWHM are of the order of those observed in NLSy1. Lower accretion rates give instead FWHM typical of broad line type 1 AGN. For very low accretion rates the BELCs would not longer exist giving an upper limit to the allowed FWHM of the BELs, consistent with observations. This limit could explain the absence of BELs in Low-Luminosity AGN. Existing optical data of LINERs are consistent with this prediction.
- In physical units, the distance at which the BELCs would form, is a steep function of both the accretion rate and the mass of the central object. The predicted relationships agree with the observed masses, FWHM, and distances (WPM99).
- We find an empirical relationship which suggests that the radiative efficiency of higher mass black holes is greater than that for lower mass black holes.

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Fig. 1.— Predicted accretion rate vs  $\text{FWHM}(r_{wind})$ ,  $\text{FWHM}(r_{max})$ , for  $m = 10^6, 10^7, 10^8, 10^9$ , and  $\dot{m}$  in the range  $\dot{m}_{min}(m) - 10$ .

Fig. 2.—  $r_{wind}$  vs  $\text{FWHM}(r_{wind})$  curves, for 4 values of the black hole mass ( $m = 10^6, 10^7, 10^8, 10^9$ : mostly horizontal curves), and 4 values of the accretion rate ( $\dot{m} = 0.01, 0.1, 1, 10$ : vertical curves). The units on the Y-axis are both in light-days (left axis) and cm (right axis). The points are the measured BELR distances and  $\text{H}\beta$  FWHM for the 19 type 1 AGN of the WPM99 sample.

Fig. 3.— Correlation between the relative radiative efficiency  $\xi$  and the measured black hole mass  $m_{meas.}$ .





